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ENSO and seasonal sea-level variability – A diagnostic discussion for the U.S.-Affiliated Pacific Islands

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With 5 Figures

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Summary

The El Niño-Southern Oscillation (ENSO) climate cycle is the basis for this paper, aimed at providing a diagnostic outlook on seasonal sea-level variability (i.e. anomalies with respect to the Climatology) for the U.S.-Affiliated Pacific Islands (USAPI).

Results revealed that the sea-level variations in the northwestern tropical Pacific islands (e.g. Guam and Marshall Islands) have been found to be sensitive to ENSO-cycle, with low sea-level during El Niño and high sea-level during La Niña events. The annual cycle (first harmonic) of sea-level variability in these north Pacific islands has also been found to be very strong. The composites of SST and circulation diagnostic show that strong El Niño years feature stronger surface westerly winds in the equatorial western/central Pacific, which causes north Pacific islands to experience lower sea-level from July to December, while the sea-level in south Pacific islands (e.g. American Samoa) remains unchanged. As the season advances, the band of westerly winds propagates towards the south central tropical Pacific and moves eastward, which causes American Samoa to experience a lower sea-level from January to June, but with six months time lag as compared to Guam and the Marshalls.

U.S.-Affiliated Pacific Islands are among the most vulnerable communities to climate variability and change. This study has identified the year-to-year ENSO climate cycle to have significant impact on the sea-level variability of these islands. Therefore, regular monitoring of the ENSO climate cycle features that affect seasonal sea-level variability would provide substantial opportunities to develop advance planning and decision options regarding hazard management in these islands.

1. Introduction

U.S.-Affiliated Pacific Islands (USAPI) are sensitive to climate variability and change. Major parts of these islands are regularly affected by the coastal surges. The sub-region's tropical and sub-tropical climate is punctuated by climatic extremes that have far reaching impacts on land-use, and serious environmental consequences. The small size of the islands, their remoteness and limited financial resources plus poor economic and social decisions have resulted in increased ecosystem and human vulnerability to disasters (Shea et al., 2001). The most vulnerable communities are impoverished peoples occupying marginal environments (such as low-lying filled mangrove swamps, urban areas of atoll islets, or steep-sloped mountain areas) with high population density and dependence on a single source of sustenance. Therefore, economic plans of these islands are dependent on the climate-sensitive sectors, and among others, the year-to-year climate variability (especially the ENSO climate cycle) has significant consequences on the overall development of these islands (Shea, 2003). For example, the 1997–98 ENSO event caused water rationing in Marshalls Islands, crop losses in Federated State of Micronesia (FSM) and other islands, and also caused significant jobs loses in many of these islands.

The existing climate literature also supports the evidence that the tropical climate variability is heavily influenced by the ENSO climate cycle. Among others, Bjerknes's (1966, 1969) pioneering studies indicated that tropical climate was strongly influenced by ENSO episodes. Later empirical studies (e.g. Ropelewski and Halpert, 1987; Chu, 1995) supported the results of Bjerknes. Lau's (1985) global climate model experiments indicate that much of the atmospheric response to ENSO is associated with the changes in sea-surface temperatures (SSTs) in the Pacific. Pacific SSTs can thus be used to forecast regional climate fluctuations, especially in the tropical Pacific area (Barnston and He, 1996; Yu et al., 1997). The state of the ENSO not only directly affects the climate in the tropical Pacific, but also affects the climate over many large regions of the world through a chain of teleconnections that take only a few weeks to occur once an El Niño or La Niña has established itself (Tribbia, 1991). Recently, Xue et al. (2000) provided some initial findings that the sea-level in the tropical Pacific contains the most essential information for ENSO (also see Xue and Leetmaa, 2000). Based on all these research findings, the year-to-year ENSO cycle has been identified as the major interannual indicator/predictor for sea-level variations in the USAPI.

While the monsoon subsystems in the western Pacific are connected to variations in sea surface temperature (SST) in the Pacific, research specifically addressing the ENSO climate cycle and sea-level variation in the USAPI is scarcely available. Therefore, the primary intention of this paper is to develop a diagnostic outlook on ENSO-based seasonal sea-level variability for the USAPI by using the teleconnections with tropical SSTs and surface wind anomalies. It is well documented in the wave literature that this surface wind stress anomaly forcing is consistent with Kelvin wave triggering (see Delcroix et al., 1991 and references therein). Based on Geosat sea-level anomalies (GSLA) and surface geostrophic zonal current anomalies (GZCA) during the ENSO event in 1986–87, the theory of equatorial wave propagation in the Pacific Ocean has already been examined in Delcroix et al. (1991). To complement the equatorial wave propagation theory, we examine ENSO-based seasonal sea-level variability from an observational perspective by taking composites of SSTs, atmospheric circulations, and sea-level deviations for the major ENSO events. Also different from Delcroix et al. (1991), we are focused on a particular region in the Pacific within the administrative boundary of USAPI, and our goal is to produce operational information on sea-level variability for real-time hazard mitigation planning for these islands. As the seasonal sea-level variations-anomalies with respect to the climatology-is the subject of inquiry here, so a brief discussion on the climatology of annual cycle of sea-level is provided in this paper.

2. U.S.-Affiliated Pacific Islands (USAPI) – Environmental settings

The USAPI include (i) Territory of Guam, (ii) the Republic of Palau (RPalau), (iii) the Commonwealth of the Northern Mariana Islands (CNMI), (iv) the Republic of the Marshall Islands (Marshalls), (v) the Federated States of Micronesia, and (vi) American Samoa. The first five islands are located in the north Pacific while the sixth one is located in the south Pacific

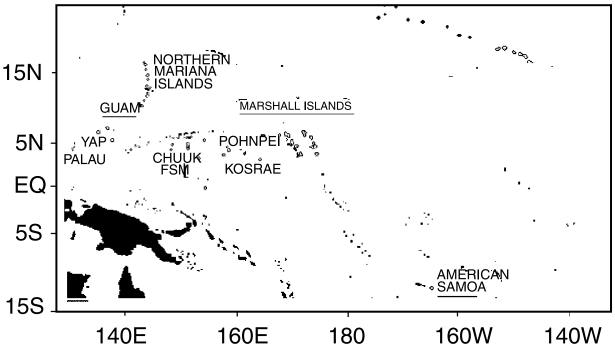

Fig. 1. Geographical locations of the U.S.-Affiliated Pacific Islands (Note that tide gauge stations *Marianas* from Guam, *Kwajalein* from Marshalls, and *Pago–Pago* from American Samoa (underlined) are taken for comprehensive composite analyses). See Table 1 for geographical details (latitude, longitude) of these tide gauge stations

(Fig. 1). Environmental settings of these islands are as follows:

(i) Guam is the largest Micronesian island, with a land area of 212 square miles and 160,796 people (est. 2002). Formed by the union of two volcanoes, northern Guam is a flat limestone plateau while the southern part is mountainous.

(ii) RPalau is the westernmost jurisdiction in Micronesia, less than 500 miles from the Philippines. It consists of several hundred volcanic islands and a few coral atolls but only nine islands are inhabited, with a population of 19,409 people (est. 2002). The land area is 188 square miles. Palau's economy is dominated by marine resources and agriculture.

(iii) CNMI forms a chain of 17 volcanic islands, stretching over 375 miles north to south, with a land area of 181 square miles. There are six inhabited islands, but most of the 77,311 inhabitants (est. 2002) live on Saipan.

(iv) Marshalls consists of two chains of 29 coral atolls and five low islands stretching several hundred miles from north to south with a total land area of 70 square miles and a population of 73,630 (est. 2002). Marshalls are developing their agriculture and marine resources.

(v) FSM consisted of three states *Chuuk*, *Yap*, and *Pohnpei*. *Chuuk State* comprises the volcanic islands in the *Chuuk* Lagoon and some 24 outer-island atolls-in all, some 290 islands. *Chuuk* is the most populous of the FSM states, with 53,595 people (est. 2000) and a land area of 49 square miles. *Kosrae State* is one volcanic island of 43 square miles with a wet tropical climate. *Yap State* consists of four volcanic islands plus 19 inhabited outer islands and atolls, with a total land area of 46 square miles. *Pohnpei State* is made up of one large volcanic island and six inhabited atolls, with most of its 133 square miles on Pohnpei Island.

(vi) ASamoa is the lone south Pacific island, which has a land area of 76 square miles and approximately 68,688 residents (est. 2002), most of whom live on Tutuila. Agriculture dominates the economy of ASamoa.

3. Data, basic indices, and method

3.1 Sea-level data

The University of Hawaii Sea-level Center (UHSLC) provides three online databases; the research quality data, fast delivery data, and the map data (http://ilikai.soest.hawaii.edu/uhslc/datai.html). The Joint Archive for Sea-level (JASL) receives hourly data from regional and national sea-level networks. The data are inspected and obvious errors such as data spikes and time shifts are corrected. Gaps less than 25 hours are interpolated. Reference level problems are referred back to the originator. If the originators cannot resolve the reference level shift, comparisons with neighboring sites or examination of the hourly residuals may warrant an adjustment. Descriptive station information and quality assessments are prepared. This research quality data set in the UHSLC is the largest global collection of quality-controlled sea-level data which is scientifically valid, reliable, and well-documented. Comprehensive data-related discussions are available in the UHSLC web site (http://ilikai.soest.hawaii.edu/UHSLC/jaslpr2/slman2.html). Also, the technical aspects of quality control procedures have been well documented in Kilossky and Caldwell (1991) and Caldwell and Kilosky (1992).

For the purpose of this study, the research quality monthly (January–December) sea-level data have been downloaded from the web site (http://ilikai.soest.hawaii.edu/uhslc/rqds.html). Geographical details (latitude, longitude) and length of data records) of the tide gauge stations located in the USAPI are listed in Table 1. The anomalies of sea-level are computed by subtracting the mean annual cycle of the sea-level variation that is estimated using data from 1975 through 1995. The missing values were replaced by long-term means. However, in case of major ENSO years, missing values were replaced with the help of values of best 'nearest neighboring stations', provided the time-series of these two stations are found to be highly correlated and statistically significant.

With the exception of American Samoa, the long term sea-level time series data confirmed that the monthly sea-level fluctuations of these north Pacific islands are significantly correlated to each

Table 1. Geographical details (latitude, longitude) and length of data records of each tide gauge station

Islands	Tide gauge stations (#)	Latitude	Longitude	Years of data records
Guam	**Marianas** (# 053)	13.44° N	144.65° E	1948–2003
RPalau	Malakai-B (# 007)	7.33° N	134.47° E	1969–2003
CNMI	Saipan (# 028)	15.23° N	145.75° E	1978–2003
Marshalls	**Kwajalein** (# 055)	8.73° N	167.73° E	1946–2003
FSM	Chuk (# 054)	7.45° N	151.85° E	1963–91
ASamoa	**Pago–Pago** (# 056)	14.29° S	170.69° W	1948–2004

Note: RPalau stands for Republic of Palau, CNMI for Commonwealth of the Northern Mariana Islands. FSM for Federated States of Micronesia, and ASamoa for American Samoa (Note that stations marked in bold are taken for a comprehensive composite analyses)

Table 2. Correlations of monthly sea-level variations in the USAPI

	Guam	RPalau	CNMI	Marshalls	FSM	Asamoa
Guam	1.00					
RPalau	0.642**	1.00				
CNMI	0.743**	0.680**	1.00			
Marshalls	0.763**	0.777**	0.661**	1.00		
FSM	0.771**	0.952**	0.808**	0.681**	1.00	
ASamoa	0.348	0.001	0.217	0.140	0.086	1.00

* Significant at 0.05 level, ** significant at 0.01 level

other (Table 2). So, findings quantifying ENSO-sea-level relationships in any of these north Pacific islands are similarly valid for other islands too. Because of longer sea-level data records of Guam and Marshalls, these two stations are taken for detailed analyses from the north Pacific. From the south Pacific, American Samoa – which has also longer sea-level data records – is taken for detailed analyses. A diagnostic discussion for the above three islands is reported in this paper. For the other three islands (RPalau, CNMI, and FSM), only a summary of results deemed to be of interest or importance is reported.

3.2 SST and wind indices for strong El Niño and La Niña years

A historical monthly field of the global SST is considered in the analyses (Smith et al., 1996). For atmospheric circulation (zonal wind at 850 hPa), the NCEP/NCAR reanalysis is used (Kalnay et al., 1996; Smith and Reynolds, 2002, and references therein). Given that there are typical characteristics of El Niño and La Niña, how are specific 'ENSO events' defined? How large must the value of the index be, and for how long must it persist in order for an El Niño or La Niña to be identified as strong or moderate? Any definitive objective procedure for classifying intensity is yet to be explored. However, a common method adapted in this study is based on the Niño 3.4 SST index (Barnston et al., 1997 and references therein). In this method, an El Niño or La Niña event is identified if the 5-month running average of the Niño 3.4 index is greater than $+0.4\,^{\circ}\mathrm{C}$ (for El Niño) or less than $-0.4\,^{\circ}\mathrm{C}$ (for La Niña) for at least 6 consecutive months (Trenberth, 1997, and references therein). According to this Niño 3.4 SST index, fifteen El Niño events are identified since 1950: 1951, 1953, 1957–58, 1963–64, 1965–66, 1968–70, 1972–73, 1976–77, 1977–78, 1982–83, 1986–87, 1990–92, 1993, 1994–95, and 1997–98, and eleven La Niña events are identified: 1950–51, 1954–56, 1964–65, 1967–68, 1970–72, 1973–76, 1984–85, 1988–89, 1995–96, 1998–2000, and 2000–01 (http://iri.columbia.edu/climate/ENSO/background).

It has been observed that many El Niño and La Niña events extend across different calendar years, and some El Niño and La Niña events persist for as many as two full years. Not all El Niño and La Niña events are of equal duration nor do they all evolve in the same way. In fact, observations indicate a fair amount of variability in the life cycles of individual El Niño and La

Niña events. Therefore, this classification would vary if based on an averaged Niño 3.4 index over different seasons. Further, it was observed that the relative classification of events would vary if the ranking were based on an index other than Niño 3.4. For example, the classification system in the Western Regional Climate Center (WRCC), which is based on the average value of the Southern Oscillation Index (SOI) for the months of June–November, provides a different list of events (http://www.wrcc.dri.edu/enso/ensodef). With this WRCC approach, the ENSO phase is determined by atmospheric pressure variation (SOI) (value of $\text{SOI} < -1.0$: strong El Niño, $\text{SOI} < -0.5$: moderate El Niño, $\text{SOI} > +0.5$: moderate La Niña, and $\text{SOI} > +1.0$: strong La Niña).

Based on (i) 5-month running average of the Niño 3.4 SST and (ii) average SOI for six months, five strong (or major) El Niño events classified are 1951, 1957–58, 1972–73, 1982–83, and 1997–98, and five strong (or major) La Niña events classified are 1964, 1973–74, 1975–76, 1988–89, and 1998–99. For identifying these strong events, all the classification methods were mutually supportive.

However, as the accuracy of ENSO strength depends on a variety of oceanic and atmospheric parameters, and while it is certainly possible to get accurate information for one parameter, it is extremely difficult to draw a common firm line in using all these oceanic and atmospheric parameters. Some problems were encountered when the moderate events were chosen. As it was difficult to get all these parameters to agree, some subjective analysis was employed to isolate moderate events from the available list. Therefore, part of the moderate ENSO classification may contain some uncertainties. Finally, five moderate El Niño events were chosen as 1963, 1965, 1969, 1974, and 1987, and five moderate La Niña events were chosen as 1956, 1970, 1971, 1984 and 1999 (also see Chowdhury, 2003).

4. Results

The findings of the study are summarized below:

4.1 Climatology of annual cycle

The observed value of sea-level seasonal indices (Fig. 2 – solid lines) of most of the northern Pacific Islands, by and large, displayed a strong annual cycle (Fig. 2a–e). In the case of Guam, a gradual increase of sea-level from January to July has been observed (Fig. 2a). Soon after the peak in July, a gradual recession starts, which extends up to December. CNMI, RPalau, and FSM also experienced similar peak and recession. The sites of Guam, CNMI (Saipan), RPalau (Malakal), and FSM (Chuuk) are situated, between latitude 5–15° N, within the equatorial trough and the North equatorial current (eastward). Therefore, the similarity of seasonal cycle of these stations is evident, with low sea-levels in the first half of the year and high sea-levels from July, typical of the northern hemisphere.

On the other hand, the Marshalls, which are located in the central North Pacific, displayed a peak in April, followed by intermittent fluctuations (Fig. 2e). After October, the sea-level receded sharply in the next few months. This Marshalls (Kwajalein) are close to Countercurrent Ridge, situated generally 3–9° N, and are usually within the North Equatorial Countercurrent (eastward). In contrast to the aforementioned western North Pacific stations, this central North Pacific station displays several peaks, with two distinct maxima in April and October, and two minima in January and September. These biannual maxima and minima are associated with the latitudinal seasonal movement near Countercurrent Ridge, cycling generally 3 and 9° N (Verstracte, 2001).

American Samoa, the lone south Pacific island, tended to show several peaks in the annual cycle (Fig. 2f). A gradual rise of sea-level was observed from January and the first peak reached in March. A second peak was observed in July due to an abrupt rise of sea-level from June. Slow and intermittent recessions followed in the later part of the year. The annual cycle of this site ASamoa (Pago–Pago) is nearly flat, with slightly higher sea-levels in March and lower sea-levels in May–June. This is typical cycle of the tropical Southern Hemisphere, due to the seasonal steric effect and the expansion (contraction) of the water column at the end of the southern summer (winter).

To quantitatively evaluate the importance of the annual cycle from these data, harmonic analysis has been performed on the monthly mean

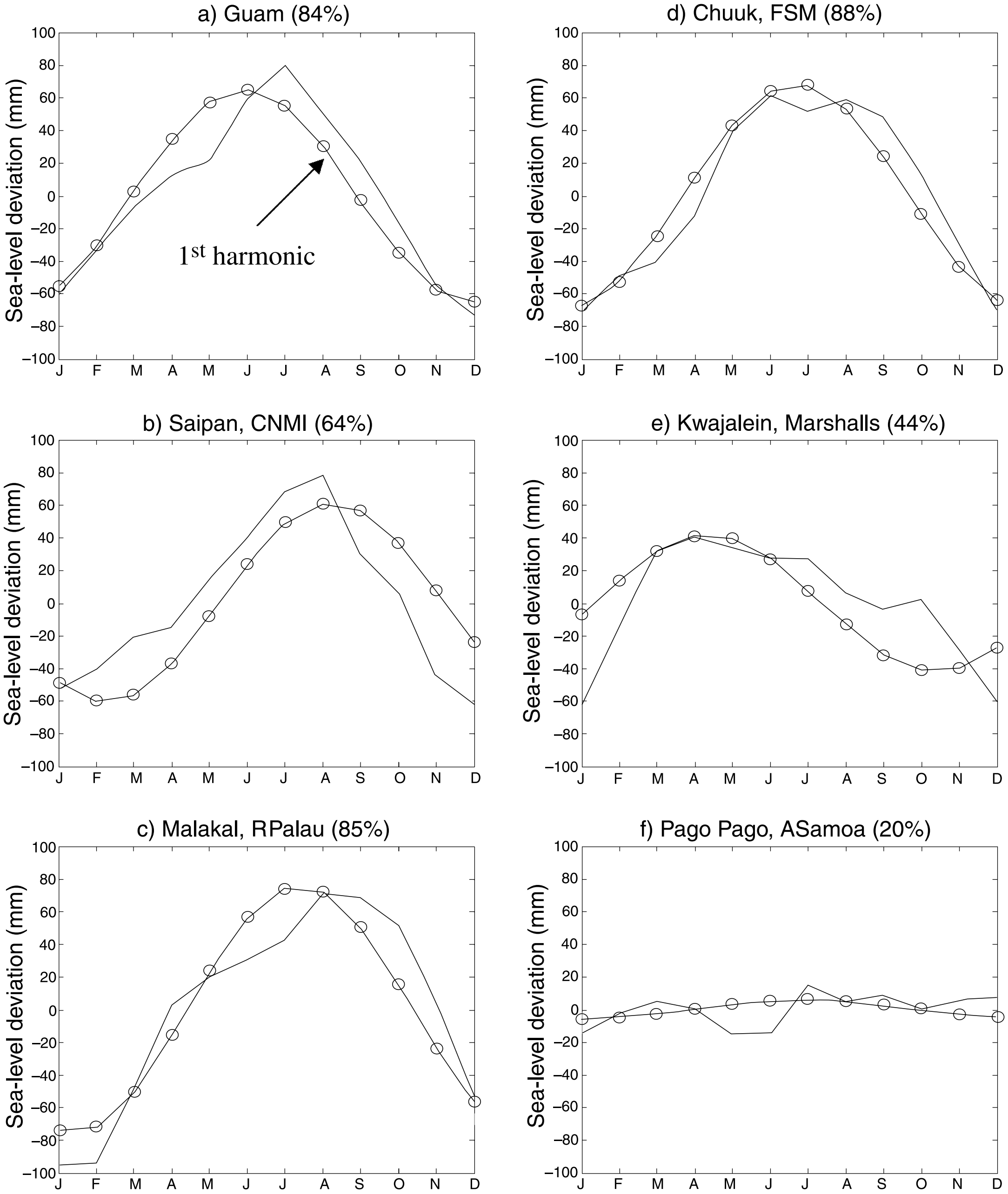

Fig. 2. First harmonic of sea-level variability. Solid line denotes long term monthly average data records in individual tide gauge stations and solid line with open circle denotes first harmonic at corresponding locations. Values in parenthesis (top) are percentage of variances explained by the first harmonics (*X-axis: Months and Y-axis: Sea-level deviations in mm*)

sea-level time-series (Fig. 2 – solid lines with open circle). Harmonic analysis consists of representing the fluctuations or variations in a time series as having arisen from the adding together of a series of *sine* and *cosine* functions (Wilks, 1995). These trigonometric functions are 'harmonic' in the sense that they are chosen to have frequencies exhibiting integer multiples of the 'fundamental' frequency determined by the sample size of the data.

The first harmonic, which represents the annual cycle, explains a considerable percentage of variance of the sea-level variability in the north Pacific islands (Fig. 2a–e). The first harmonic for all Islands explains 44–88% of the variance. For the westernmost islands in the north Pacific (Guam, CNMI, RPalau, and in FSM), maximum rise of sea-levels occurs in summer months (June–August). For the Marshall Islands, the annual cycle appears to peak in April (Fig. 2e).

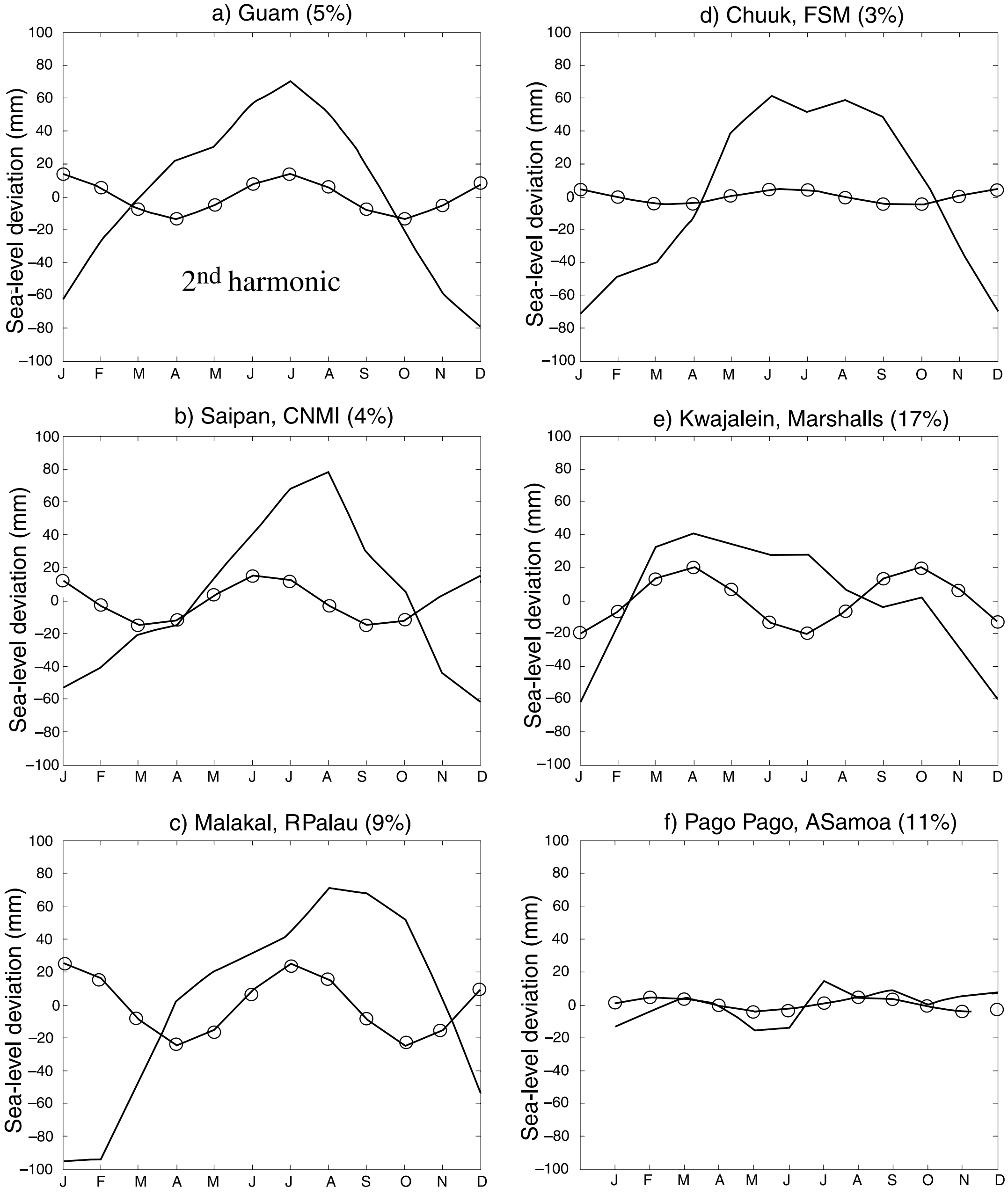

Fig. 3. See as Fig. 2, except for second harmonic of sea-level variability

The annual cycle is relatively weak in American Samoa (only 20% variance) (Fig. 2f). The second harmonic (Fig. 3), which represents the semiannual cycle, adds to the variance explained at Marshalls (17%) and American Samoa (11%) (Fig. 3e and f).

4.2 El Niño/La Niña events and sea-level deviations

Figure 4 represents the monthly sea-level deviations during ENSO events. Because ENSO usually starts to develop in summer, reaches its peak phase in the following winter, and gradually weakens through the next spring, a composite of seasonal variations of sea-level is made from July to the following June. In the cases of Guam and the Marshalls, the monthly average sea-level shows large and negative deviations during strong El Niño events (Fig. 4). This is very distinct from the time of onset of events (i.e. summer) and continues up to March of the following year. Significantly lower than average sea-level was recorded in these months during the major

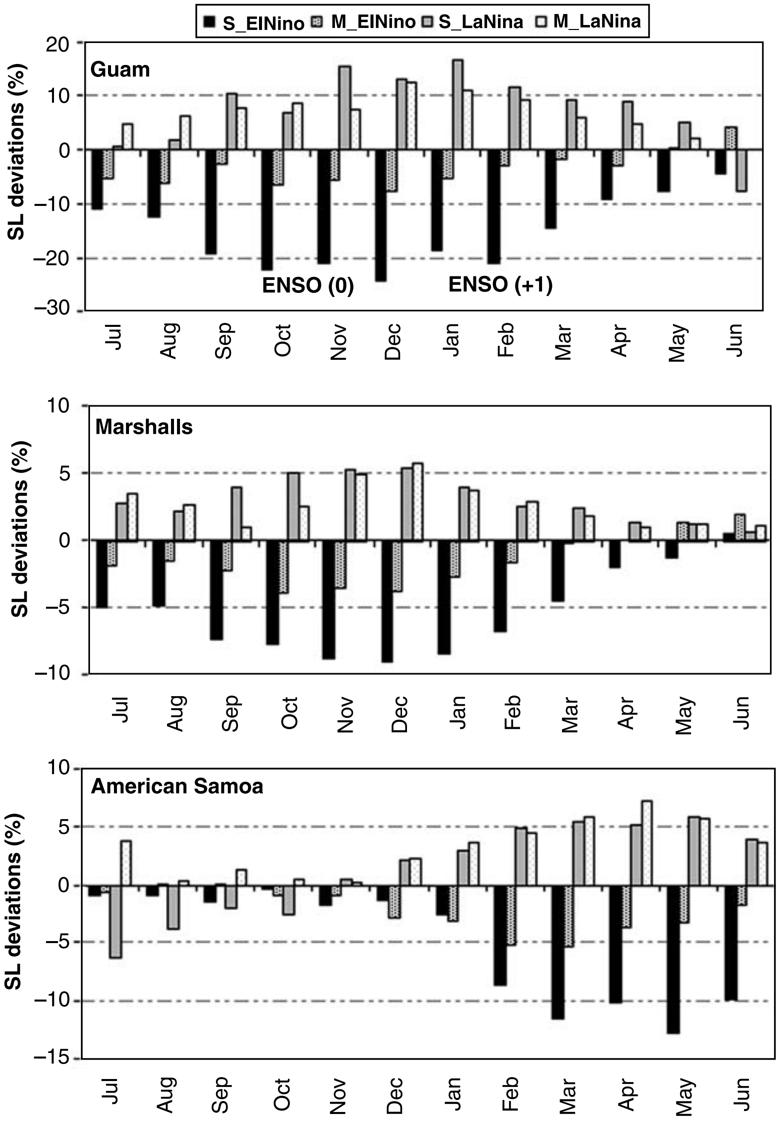

Fig. 4. Composites of monthly sea-level deviations from the normal during the ENSO years starting from July and extending to June of the following year (*X-axis: Months, and Y-axis: Sea-level* (*SL*) *deviations in percentages*). Strong (S) El Niño years: 1951, 1957–58, 1972–73, 1982–83, and 1997–98/ Strong (S) La Nina years: 1964, 1973–74, 1975–76, 1988–89, and 1998–99/Moderate (M) El Niño years: 1963, 1965, 1969, 1974, and 1987/Moderate (M) La Niña years: 1956, 1970, 1971, 1984, and 1999

or strong El Niño years. The moderate El Niño years also recorded lower than average sea-level – only the magnitude being smaller relative to strong El Niño. Thus, the strength of El Niño on sea-level variations (fall/rise) in Guam and the Marshalls is evident. Similar, but opposite, relationships exist in La Niña years; that is, both the strong La Niña and moderate La Niña years recorded higher than average sea-level.

For American Samoa, there is no pronounced variation in sea-level from July to December during strong and moderate El Niño years (Fig. 4). However, consistent with the previous findings for North Pacific Islands, El Niño years produced pronounced fall of sea-levels during January to June while La Niña years showed considerable sea-level rise during the same time period. Under the influence of ENSO, the trend of sea-level variations in American Samoa displays a couple of months delay with respect to sea-level variations in Guam and Marshalls. The diagnostic discussion (i.e. ENSO, SST/circulations patterns) for this lagged response in American Samoa are explained in the following section.

4.3 ENSO, SST/circulation, and sea-level variability – diagnostic discussion

Composite averages of SSTs and surface circulation anomalies for five strong El Niño (SE) years *minus* five strong La Niña (SL) years are presented in Fig. 5. As mentioned before, ENSO usually starts to develop in summer; so, July–August–September (JAS) is the target season

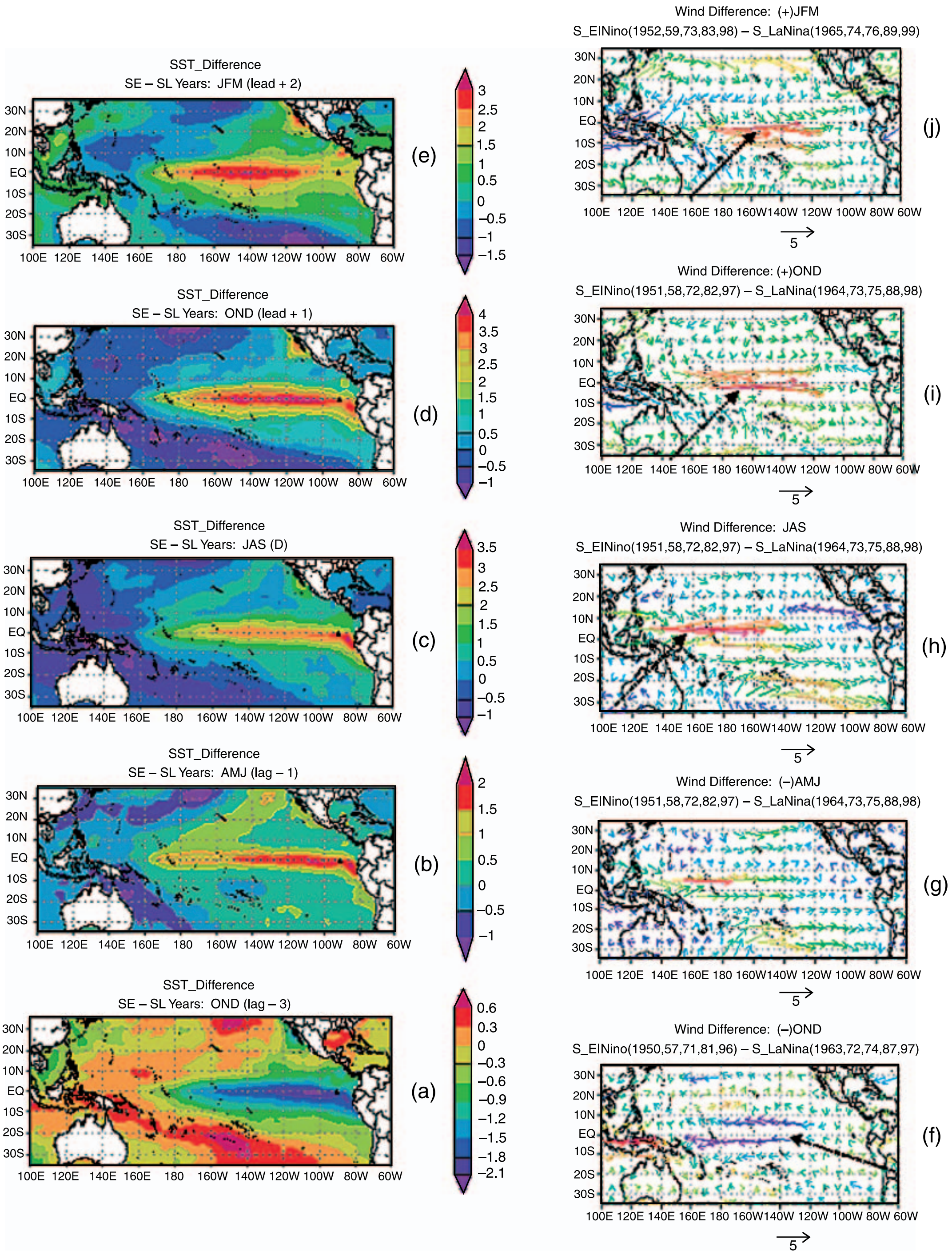

Fig. 5. Composites of SST (°C) and surface wind (m s^{-1}) anomalies for the strong El Niño *minus* strong La Niña (SE–SL) years (SSTs are in *left panel from* (*a*) *to* (*e*) and Surface winds are in *right panel from* (*f*) *to* (*j*). (Note: JAS is the target season, lead (+) *means* after JAS and lag (−) means before JAS; *OND* October–November–December, *JFM* January–February–March, *AMJ* April–May–June, and *JAS* July–August–September)

here. Starting from the previous-OND (3-season lag or lag −3 with respect to JAS) and extending up to +JFM (2-season lead or lead +2 with respect to JAS), five composites are shown.

Figure 5 shows that, as compared to SL, the average warming of SSTs in the region of equatorial central/eastern Pacific is much higher during the SE years (left panel: b–e). The warming of tropical SSTs starts from the preceding AMJ (lag −1), strengthens through OND (lead +1), and continues up to JFM (lead +2). Looking back from the OND (lag −3) (Fig. 5a: left panel) of previous year, the tropical SSTs slowly fluctuate across the Niño 3.4 and Niño 3 regions in such a way that immediately before SE, SSTs are cooler than average in these regions during OND (lag −3) and JFM (lag −2) (JFM composite is not shown in Fig. 5).

Figure 5 (right panel: f–j) shows the differences of atmospheric circulations between the strong SE and SL. The SE years feature stronger surface westerly anomalies in the equatorial western/central Pacific than in the SL years. Initially in OND (lag −3), the tropical easterly winds are active (Fig. 5f: right panel). As the season advances, the westerly anomalies that developed in the western Pacific became active in AMJ (lag −1), gradually strengthen and move eastward in JAS (lag 0: target season), and further continue to propagate eastward to the equatorial eastern Pacific by JFM (lead +2) (Fig. 5g–j). Due to the reversal of the prevailing wind direction, piled-up water in the tropical western Pacific flows eastward toward South America as triggered by oceanic Kelvin waves (also see Delcroix et al., 1991). As a result, the North Pacific Islands (e.g. Guam and Marshalls) start experiencing significant drop in sea-level from July of year (0) to March of year (+1) (Fig. 4). However, as the year advances, the band of westerly anomalies shifts southward and strengthens in the region of 0° to 10° S by JFM (lead +2) (Fig. 5j). As a result of the shift of surface wind patterns, American Samoa starts experiencing sea-level drop from January (+1) and continues up to June (+) (Fig. 4). It is important to note here that Guam and American Samoa are located near 15° latitude (15° N and 15° S), not under the strong influence of equatorial currents.

Consistent with the previous finding for strong El Niño, the moderate El Niño years also experienced weaker westerly wind (not shown) that caused a drop in sea-level. Therefore, sea-level variations in the north Pacific islands correspond to the strength of ENSO – stronger events result in a larger decrease in sea-level. Similar but opposite linear relationships were observed with the strength of La Niña too.

It has been found from the above example that sea-level variations in the tropical Pacific islands are distinct in El Niño and La Niña years. But are these differences statistically significant? To answer this question, we used the non-parametric Mann-Whitney tests (Chu, 2002; Wilks, 1995). Because of the smaller sample size for each data batch, a non-parametric test is justified. To perform this test, the two data batches pertinent to El Niño and La Niña events are pooled from the samples. The null hypothesis is that the two batches come from the same distribution. The Mann-Whitney tests indicated that the sea-levels for Guam and Marshalls during the El Niño years are lower than the La Niña years with statistical significance at the 5% level for the seasons JAS and OND (*p*-value 0.009 and 0.016 respectively). Other seasons remained statistically insignificant at the specified test level. In addition, there was no clear evidence of significance at American Samoa.

4.4 Equatorial waves and sea-level variability

Although the wave analyses are not the subject of inquiry in our study; it is, however, worth comparing our findings with other available results. As mentioned before, Delcroix et al. (1991) provided a comprehensive picture on equatorial Kelvin and Rossby waves' propagation theory from the 1986–87 GSLA and GZCA data. They showed that the first notable equatorial GSLA patch (rise), occurred in November–December 1986, which is consistent with the equatorial downwelling induced by westerly wind anomaly located west of 170° W. The second GSLA patch (drop) occurred in March–April 1987 and is related to the easterly wind stress anomaly centered near 170° E. The third notable GSLA patch (drop) starts in early June 1987 and stops at the beginning of July 1987, which Delcroix et al. (1991) suggested is due to the change in the wind-stress anomaly, from westerly to easterly in early June 1987 near 170° E (also see McPhaden et al., 1990).

Comparing with Delcroix et al. (1991), our composite analyses from 5 major ENSO years also display similar consistency indicating that an active easterly wind exhibited initially in OND (lag −3) and continued up to JFM (lag −2), before the onset of ENSO. In AMJ (lag −1), the westerly became active and gradually strengthened in JAS (lag 0), during the onset of ENSO. Because of the change of this wind-stress anomaly – from westerly to easterly – the northwestern Pacific Islands start experiencing significant drop in sea-level from July (0).

5. Summary of findings

Following an overview of the climatology of the tide-gauge stations in the USAPI by quantitative methodology, the effects of ENSO and SST/circulations are studied by composite methods. Findings are summarized as follows:

i) The observed value of long-term monthly sea-level variability of most of the northern Pacific Islands by and large displayed a strong annual cycle with a gradual increase of sea-level from January to July and recession from July to December. On the other hand, the lone south Pacific island (American Samoa), tended to show several peaks in the annual cycle. Results of harmonic analyses show that the annual cycle (first harmonic) explained a considerable percentage of variances of the sea-level variability in the north Pacific islands. The annual cycle is extremely weak in American Samoa; however, the semi-annual cycle (second harmonic) adds considerably to the variances in this case.

ii) ENSO has a strong impact on the sea-level variability of USAPI. In general, El Niño (either strong/or moderate) corresponded to low sea-level, and La Nina (strong/moderate) corresponded to high sea-level in the USAPI. For Guam and Marshall Islands, the Mann-Whitney nonparametric tests indicated that the difference in sea-level variations between El Niño and La Niña is statistically significant (5% level) for the seasons JAS and OND.

iii) As compared to strong La Niña years, the average warming of SSTs in the region of equatorial central/eastern Pacific is much higher during the strong El Niño years. The warming of tropical SST starts from the preceding AMJ, strengthens through OND, and continues up to JFM of the next year. The differences of atmospheric circulations show that the strong El Niño years feature stronger surface westerly winds in the equatorial western/central Pacific, which causes north Pacific islands (e.g. Guam and Marshalls) to experience lower sea-level from July to December, while the sea-level in south Pacific islands (e.g. American Samoa) remains unchanged. As the season advances, the band of westerly winds propagates towards the south central tropical Pacific and moves eastward, which causes American Samoa to experience a lower sea-level from January to June with six months time lag, as compared to Guam and Marshalls.

6. Concluding remarks

Pacific Island communities are vulnerable to coastal surges and the most vulnerable communities are impoverished peoples occupying marginal environments. Among others; the ENSO climate cycle has significant consequences on the overall development of these islands. Therefore, advance information on seasonal sea-level variability can contribute significantly in hazard preparedness actions for the people of these islands. It is not only prudent but also essential that 'ENSO-based sea-level variability' be thoroughly assessed on a continuous basis for the well-being of the people of these small islands. In order to fulfill this objective, the PEAC was established in August 1994 as a multi-institutional partnership to conduct research and produce information products on climate variability related to the ENSO climate cycle in support of planning and management activities of the economic and environmental sectors in the USAPI. The PEAC has already started publishing model-based sea-level forecasts for these islands (available at http://lumahai.soest.hawaii.edu/Enso/peu/update.html). The enhancement of this seasonal sea-level information would offer the potential of greater latitude in planning and decision options regarding hazard management in the USAPI.

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